# The Effect of Rate of Strain on Soil Strength

D. Hampton, Graduate Assistant

E. J. Yoder, Research Engineer

Joint Highway Research Project
Purdue University

## INTRODUCTION

The fact that the compressive strength of a soil is a function of the time required to reach the failure load has long been recognized. However, this area of soil mechanics has not been extensively explored and much work remains to be done, in order that the effects of this phenomenon can be properly evaluated. The specific areas where this information would be of the greatest benefit are as follows:

a. stability of slopes subjected to earthquakes and other forms of transient loading,
b. transmission of forces from explosions through soils,
c. design of highway pavements, and
d. design of airfield pavements.

*Stability of slopes*—In areas where there are possibilities of earthquakes, it is of the utmost importance to investigate the stability of slopes, both natural and man-made, under transient conditions. Such an investigation is especially necessary when failure of the slope in question would be disastrous. Earthquake shocks induced in the earth represent transient loading conditions, and critical slopes in such areas should be designed and analyzed on this basis.

*Transmission of forces from explosions*—The transmission of forces from explosions through soil, due to the short time of loading, is another example showing that earth structures subject to such forces should be designed and analyzed on the basis of transient loading tests, as should structures imbedded in the soil. Such a rigorous study would be valid only for critical military installations; consequently, this cause of transient loads in soil will not be given further consideration.

*Design of highway pavements*—It is generally recognized that the stress-strain characteristics of pavements are a function of the rate of strain. This can be readily seen by observing the condition of pavements at critical sections along a given route.

From such studies, it has been found that road intersections, uphill grades and other sections where traffic is required to move slowly, or to stop, show distress much more rapidly than their counterparts, i.e., open road, free of stops, and down-hill grades. This is believed to be caused by the difference in speed of travel over the aforementioned sections. As a result, there is much need of a comprehensive study on the effect of rate of strain on the behavior of soils.

On the basis of the above, a different design criteria, as well as specifications for the materials used in construction, should be applicable to each case. If there is a great difference in the design based on the two methods of loading, a substantial savings in cost would be obtained by altering the design accordingly.

*Design of airfield pavements*—Because of the high speed at which airplanes travel over runways, they are subjected to transient loading conditions which are vastly different from the relatively static conditions to which the aprons, taxiways, and ends of runways are subjected. Hence, it is necessary to evaluate the difference in stress-strain characteristics under both transient and static loading, for all materials involved, in order to obtain the most economical as well as the best design.

## PURPOSE AND SCOPE

These examples constitute a few of the reasons why a study to better understand the effect of time of loading on the strength of soil is easily justified from an engineering viewpoint. Consequently, the primary purpose of the research reported herein was to investigate the strength properties of a clay and silty clay under conditions of transient loading. Specifically, the aim was to attempt to ascertain the relationship between rate of strain and unconfined compressive strength at various moisture contents and densities. Also, it was hoped to relate the aforementioned variables to the modulus of deformation.

Rate of strain was considered the most important variable, and it was studied from 0.55 in./min. to 1780 in./min. Soil texture was a second variable; two fine-grained soils of significantly different chaacteristics, a silty clay and a clay, were chosen. All soils are native to Indiana.

The factors of moisture content and dry density were also of prime importance. Three compactive efforts were used and specimens were molded and tested on both sides of the optimum moisture content, O.M.C., of each compactive effort.

## DEFINITIONS

Since the terminology used in this report may differ from that of other investigators, it is necessary that it be defined.

a. *A slow transient compression test* is one in which the rate of strain lies within the range of 0.45 in./min. to 0.6 in./min.

b. *A medium transient compression test* is one in which the rate of strain lies between 11.0 in./min. and 15.5 in./min.

c. *A fast transient compression test* is one in which the rate of strain is greater than 250 in./min.

d. *Time of loading* is defined as the difference in time between the start of a loading test and the time at which the maximum compressive stress is reached.

e. *Modulus of deformation* is a secant modulus defined as the slope of a line from the origin through the point on the stress vs. strain curve at which the stress is one-half of the compressive strength. Or, if the initial part of the stress vs. strain curve is straight, it is the slope of this portion of the curve.

f. *Rate of strain* is defined as the deformation at failure divided by the time required to reach failure.

g. *Strength ratio,* $S_u$, is defined as the ratio of the strength, for a given rate of strain, to that for a slow transient test at the same moisture content and for the same compactive effort.

h. *Modulus of deformation ratio,* $M_D$, is defined as the ratio of the modulus of deformation for a given rate of strain to that for a slow transient test at the same moisture content and for the same compactive effort.

i. *Strength,* in this report will always apply to the axial load per unit area required to produce failure in an unconfined compression test.

## DESCRIPTION OF MATERIALS

Two soils were selected for purposes of this study: (a) a red-colored clay derived from limestone, and (b) a brown glacial silty clay, pedologically classified as Crosby, "B" horizon. These soils were selected primarily on the basis of their difference in plasticity. It was believed that the plasticity characteristics of the soil would be a determining factor in the effect of the rate of strain on these materials.

The clay was from a location in southern Indiana and is the product of the weathering of rock of Mississippian-age (1).* The soil is rather

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* Numbers refer to references in the bibliography.

well graded, highly plastic, very tough near the plastic limit, and has a very high dry strength. It has a liquid limit of 72 per cent, a plasticity index of 48.9 per cent, and is classified as CH by the Unified Soil Classification System (2). Pedologically, this material is classified as Frederick, and exists in a profile as shown in Reference (3).

The silty clay is an abundantly distributed material in north-central Indiana. The soil is well graded, of medium plasticity, tough near the plastic limit, and has a high dry strength. Its liquid limit is 35.5 per cent, it has a plasticity index of 15.4 per cent, and is classified as CL by the Unified Soil Classification System. The profile of this Crosby "B" soil is shown in Reference (3).

## APPARATUS AND PROCEDURE

Specimens were molded from properly prepared soil, utilizing the Harvard Compaction Apparatus. This apparatus produces specimens 2.816 inches long and $1\frac{5}{16}$ inches in diameter. The volume of the compaction cylinder is 1/454th of a cubic foot which means that the weight of the compacted specimen in grams is numerically equal to the unit weight in pounds per cubic foot.

The compactive efforts used were 10 layers at 50 blows per layer, which approximate the Modified AASHO, and three layers at 25 blows per layer which gave dry densities comparable to the Standard AASHO test. The third compactive effort varied depending on the soil being tested. The latter was necessary in order to obtain significant differences in the dry densities obtained from the three compactive efforts. For the Crosby "B" soil, the intermediate compactive effort was ten layers at 25 blows per layer while that for the Frederick Limestone soil was ten layers at ten blows per layer.

Each blow was applied through a tamper consisting of a ½" diameter brass rod equipped with a handle inside of which there was a 40-pound compressed spring (Figure 1). The operator applied just enough force to "break" the spring and then released it. In this manner a force of 40 pounds was applied per blow. The action of this compactor is held to more nearly approximate the kneading action of a sheepsfoot roller than do dynamic compaction methods.

*Unconfined compression tests*—The unconfined compressive strength tests were run on either the hydraulic loading apparatus or the impact loading apparatus depending upon the rate of strain desired (Figures 2 and 3). The hydraulic loading apparatus consisted of a constant volume hydraulic pump connected to a hydraulic cylinder through values by which the volume of liquid delivered to the cylinder could be controlled.

**Figure 1. Specimen in the process of being molded.**

Thus, by properly positioning the valves the speed of the machine could be controlled, and the desired rate of strain obtained.

The dynamic loading apparatus consisted of a ten-pound weight dropped 39 inches upon a piston which applied the load to the specimen. In order to prevent damage to the loading frame and measuring instruments, a spring was inserted atop the loading piston. A second advantage, and of equal importance, is that the elasticity of the spring caused the weight to bounce, whereupon it was caught before it could again come in contact with the piston.

A hollow pipe, suspended from the top of the wall, was used as a guide for the falling weight, and the weight had a hole in the center.

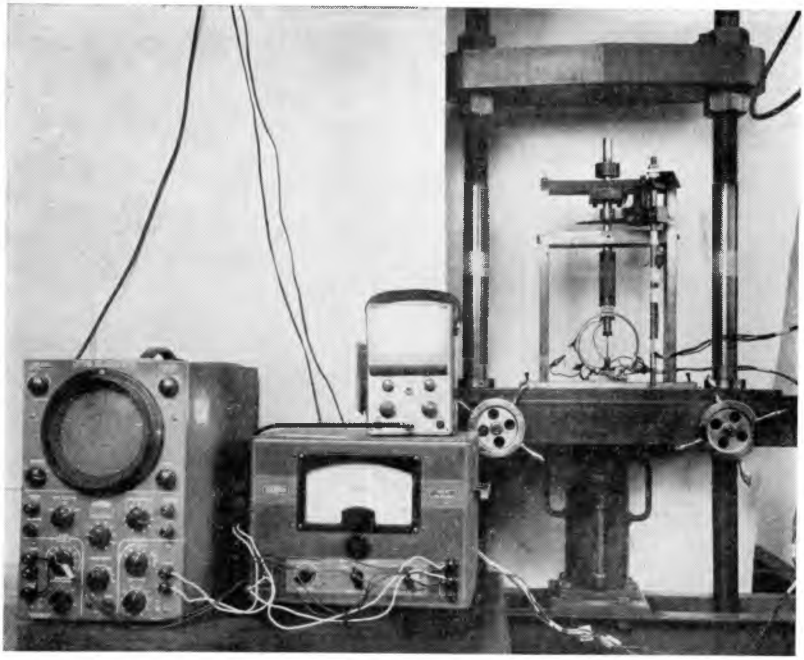


**Figure 2. Setup for slow and medium transient tests, utilizing the hydraulic loading apparatus.**

In all unconfined compression tests, a rubber membrane was placed around the specimen and secured tightly to the loading head and base. Also, the loading frame was leveled in order that the load would be uniformly applied to the sample.

*Collection of data*—Low voltage differential transformers were employed to measure the load as well as the deformation during the compression process. In this type gauge the output voltage of the secondary coil which is excited by a primary coil is proportional to the displacement of a magnetic core within these coils.

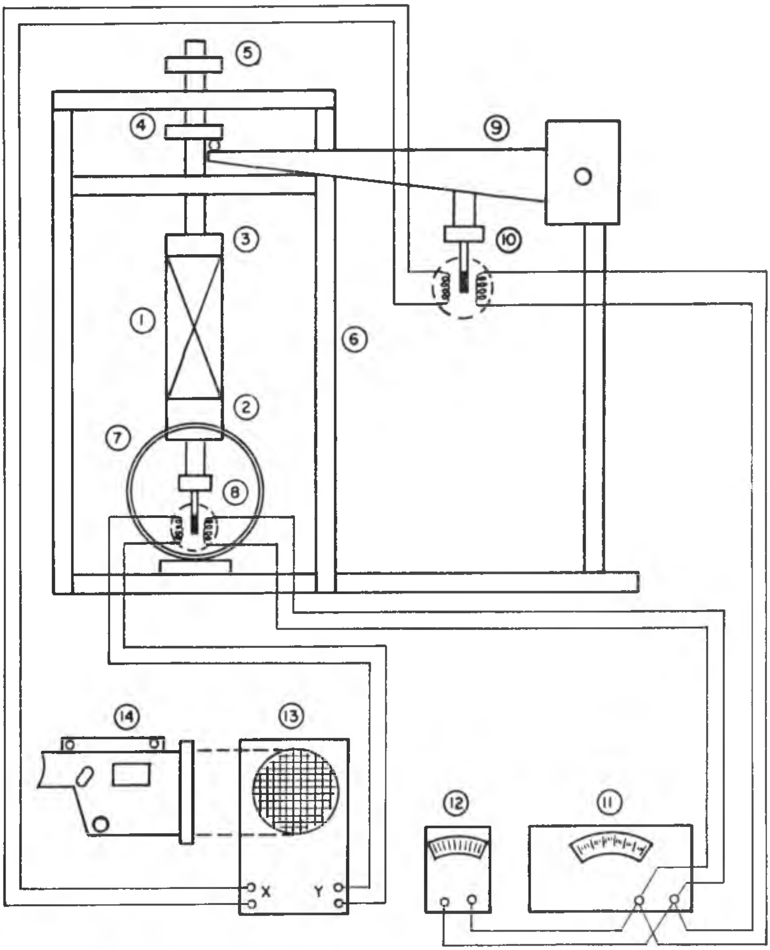
A schematic diagram of the load and deformation apparatus is shown in Figure 4. It can be seen that as the proving ring deforms the position of the core moves relative to the primary and secondary coils. Also, as the arm of the strain gauge deflects, the core contained therein moves relative to its primary and secondary coils. These movements produce changes in the output voltage of these two instruments, which can be measured. An audio oscillator operating on a frequency of 2,000 cps. was used to energize the transformers.

To record the changes in stress and strain during the process of the test a Du Mont Cathode-Ray Oscilloscope was used. In this study the

**Figure 3. Impact loading apparatus used for fast transient tests (instrumentation not shown).**

deflection of the trace was made proportional to the output of the differential transformers.

For the medium and fast transient tests the Du Mont Oscilloscope Record Camera, Type 297, was used to record the trace on the oscillograph. Operating on the Polaroid-land principle, it produced a finished oscillogram 60 seconds after exposure. However, for the slow transient test, the load vs. deformation diagram, oscilloscope trace, was drawn directly on the oscilloscope screen, with a grease pencil, during the progress of the test. Utilizing the grid on the face of the oscilloscope, this trace was transferred to a data sheet.




① SOIL SPECIMEN
② LOADING HEAD FOR PROVING RING
③ LOADING HEAD FOR SPECIMEN
④ STRAIN DATUM
⑤ STRAIN - STOP
⑥ FRAME
⑦ LOAD GAGE
⑧ DIFFERENTIAL TRANSFORMER
⑨ STRAIN GAGE
⑩ DIFFERENTIAL TRANSFORMER
⑪ AUDIO OSCILLATOR
⑫ VOLTMETER
⑬ OSCILLOSCOPE
⑭ OSCILLOSCOPE RECORD CAMERA

**Figure 4. Schematic diagram of test setup.**

## DISCUSSION OF RESULTS

*Strength*—Essentially, the effects of rate of strain on the unconfined compressive strength of the clay and the silty clay was the same. Therefore, in deference to the limited space available, only the effects of rate

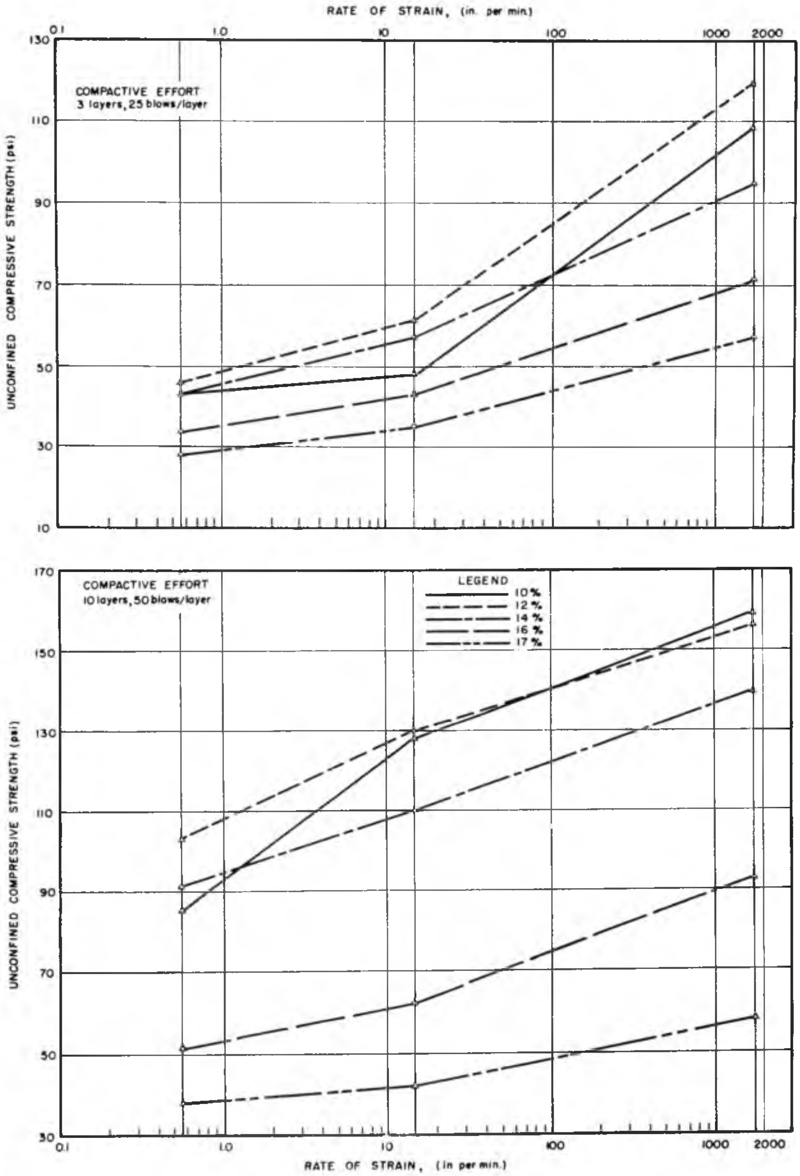



**Figure 5. Rate of strain vs. unconfined compressive strength—silty clay.**

of strain on the unconfined compressive strength of the silty clay is graphically presented (Figure 5). However, the following discussion will include the clay as well as the silty clay.

By observing Figure 5, it can be seen that for a given compactive effort and moisture content, increasing the rate of strain produced a significant increase in the strength of the soils. A study of the aforementioned figure also shows that as the compactive effort was increased the effect of changes in moisture content on the unconfined compressive strength became more significant.

For both soils, the strength ratios for the lower compactive effort were greater than those for the intermediate and highest compactive effort, for the range of moisture contents tested. For example, it was found that the strength of the lower compactive effort specimens tested under fast transient conditions always exceeded by more than 100 per cent the strength of slow transient test specimens prepared under the same conditions of moisture content and density. However, the intermediate and highest compactive efforts showed much less change in strength over the same range of rate of strain (maximum increase of 89 per cent but generally a lot less).

For both soils, the maximum strength occurred at a moisture content less than optimum, regardless of the compactive effort or rate of strain. Also, there was a rapid decrease in strength for a given increase in moisture content after optimum strength was reached.

However, an increase in moisture content had an opposite effect on the strength ratio as determined for the clay and the silty clay. As the moisture content increased, the strength ratio tended to increase for the clay, while the converse was true for the silty clay. The decrease in strength ratio as the moisture content increases, for the silty clay, was probably due to the greater effect of pore water pressures which would tend to decrease the strength of the samples.

By observation of Figure 5 it can be seen that the 10 per cent curves are out of line with the remainder of the data. This is probably due to the fact that the specimens were failing, partially at least, by crumbling rather than shear, due to their low moisture content.

*Modulus of deformation*—The effect of rate of strain on the modulus of deformation of the clay and the silty clay was markedly different. Therefore, as an aid to the following discussion the aforementioned relationship, for the clay and silty clay, is presented in Figure 6. The compactive effort, in both instances, approximated the Modified AASHO compaction test.

From the aforementioned figure it is apparent that moisture content plays a large part in determining the modulus of deformation of both soils. It is also apparent that as the rate of strain increases, the effect of moisture content on the modulus of deformation also increases.

For the silty clay, Figure 6, it appears a significant increase in modulus of deformation, due to an increase in rate of strain, was obtained

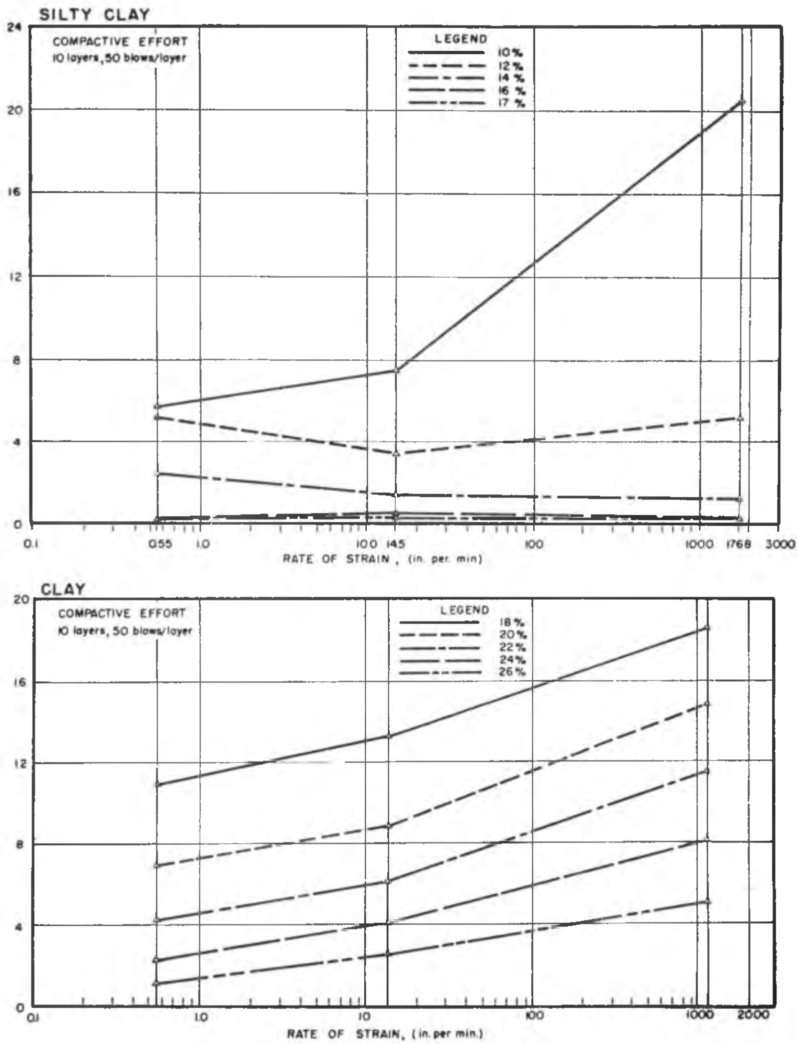



**Figure 6. Rate of strain vs. modulus of deformation.**

only for the specimens compacted at approximately 10 per cent moisture —this was true for all compactive efforts. As regards moisture contents of 12 per cent or above, it appears that an increase in the rate of strain will not produce a significant increase in the modulus of deformation. In fact, for high moisture contents and densities there was found a slight decrease in modulus of deformation with an increase in rate of strain.

For the clay soil there was also a substantial decrease in modulus of deformation for a given increase in moisture content and a given rate of strain (Figure 6). This condition was more pronounced the greater the compactive effort.

From Figure 6 the effect of rate of strain and moisture content on the modulus of deformation can be observed. In contrast to the silty clay, it is apparent that the rate of strain is an important factor in determining the modulus of deformation of the clay specimens. This was true for all compactive efforts and moisture contents tested.

Finally, in contrast to the silty clay, there was a tendency toward an increase in $M_D$ ratio with an increase in moisture for the clay. The converse was true for the silty clay.

## SUMMARY OF RESULTS

In both the clay and silty clay, a significant increase in unconfined compressive strength occurred with an increase in rate of strain for all compactive efforts and all moisture contents tested. However, with the silty clay, as the moisture content increased, the strength ratio decreased, while for the clay the converse was true.

In both the clay and the silty clay the strength ratios for the fast transient test were greater for the lowest compactive effort. No definite relationship could be established for the medium transient tests between the strength ratios and the compactive effort.

In both the clay and the silty clay, the moisture content proved to be more significant than the increase in rate of strain, as regards affecting the unconfined compressive strength. This tendency becomes less as the compactive effort decreases.

Moisture content has a great effect on the modulus of deformation of the silty clay as well as the clay. This condition is more pronounced the higher the compactive effort and the higher the rate of strain. Furthermore, for the clay soil, increasing the rate of strain produced a measurable increase in the $M_D$ ratio, but this was not the case for the silty clay. Both soils also showed that moisture content has a more significant effect on the modulus of deformation than did rate of strain, but this tendency decreased as the compactive effort decreased.

On the basis of these tests, it must be concluded that to obtain significant increases in strength or modulus of deformation, at a given moisture content and density, it takes a rate of strain approximately equivalent to fast transient conditions. Also, increasing the rate of strain was most effective in increasing the strength of soils at low densities, and as the rate of strain increased the strain at failure decreased.

The phenomenon investigated is due to time lag, i.e. a certain time being required for the development of shear planes from which failure results.

## APPLICATIONS TO HIGHWAY AND AIRPORT PAVEMENTS

Structural failure in flexible pavements may be due either to excessive shear stresses, excessive deformation brought about by consolidation, or fatigue failures. For flexible pavements, shear failures are quite common. However, excessive deformation caused by repeated loads also results in considerable distress.

Because shear failures are caused by exceeding the shearing resistance of the soil, and because it has been determined in this study that the shear strength may be increased considerably when soils are subjected to transient loads, the chances of shear failures in pavements designed on the basis of slow tests but which are subjected to transient loads is reduced. Following the same reasoning, considering shear failures which occur at the edges of flexible pavements due to the high concentration of stress at these points, better performance should be obtained from sections of the pavement where travel is free flowing than at intersections and other points along the route where vehicles are required to proceed slowly or to stop.

Due to the fact that limiting deflection rather than ultimate strength is generally the criteria for design of highway and airport pavements, the effect of rate of strain on the modulus of deformation is the critical factor, in this respect. The data indicate that for silty clay soils, slow tests can be used to determine the modulus of deformation; but, if this method is employed in the determination of the modulus of deformation of a clay, misleading results may be obtained. The error, however, will be on the conservative side.

On the basis of the data obtained, it can be said that as the plasticity increases, the effect of rate of strain on the modulus of deformation increases. From the information presented, it is apparent that the effect of rate of strain on the modulus of deformation of silty clay is small; and, when this material has a high density and high moisture content, it is negligible.

This study also shows that, for certain soils, as the rate of strain is increased the character of the soil (physical properties) becomes less important, and strength is principally a function of the rate of strain and the moisture content. This indicates that if moisture content is controlled, soils of lower quality can be utilized for subgrades under pavements where fast moving loads are anticipated.

Also, for properly designed pavements, the deflections resulting from fast moving loads are less than those for the same material subjected to slow moving loads. This would require more repetitions of load to cause fatigue failure in pavements subjected to fast moving loads. Along this same line of reasoning, it can be said that pavements subjected to fast moving loads should pump less than those subjected to slow moving loads because the deflection of the pavement in the latter instance will be greater.

In summary, it should be emphasized that the use of transient load tests for the design of structures subjected to fast moving loads may result in a great saving in time and money. However, where an extensive testing program is not feasible, some of the items enumerated may be qualitatively taken into consideration.

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